

ON THE MAXIMAL QUANTITY OF PROCESSED INFORMATION IN THE PHYSICAL ESCHATOLOGICAL CONTEXT

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Abstract

An estimate of the maximal informational content available to advanced extraterrestrial or future (post)human civilizations is presented. It is shown that the fundamental thermodynamical considerations may lead to a quantitative estimate of the largest quantity of information to be processed by conceivable computing devices. This issue is interesting from the point of view of physical eschatology, as well as general futurological topics, like the degree of confidence in long-term physical predictions or viability of the large-scale simulations of complex systems.

1 Introduction

The problem of intelligent information processing in the ever-expanding universe has recently been investigated by several authors (Krauss and Starkman 1999; Čirković and Bostrom 2000). These considerations have entered a new phase, building upon advances in observational cosmology and the strong foundations of the pioneering studies in cosmological prediction by Rees (1969), Dyson (1979), Frautschi (1982), Tipler (1986) and Barrow and Tipler (1986). In the same time, interest in the fundamental physical limits of *computation* has grown, largely motivated by tremendous advances in computer science (e.g. Lloyd 2000). Continuation of such trend of technological progress will lead humanity, sooner or later, into a stage of highly advanced galactic civilization, in recent years conventionally dubbed the *posthuman* era. Apart from the epochal importance of any such possible development for biological and social sciences, it has a strong bearing on the nascent astrophysical discipline of physical eschatology, for the reasons suggested boldly by Dyson (1979), when he wrote:

It is impossible to calculate in detail the long-range future of the universe without including the effects of life and intelligence. It is impossible to calculate the capabilities of life and intelligence without touching, at least peripherally, philosophical questions.

Certainly, the most important property of intelligence is its capacity for information processing. As it has been recognized for a long time, this form of information processing is still entirely within limits of physical, specifically thermodynamical, laws. This

conclusion does not necessarily entail reductionism, since consciousness may still contain uncomputable and therefore irreducible elements *in addition* to the conventionally established ones (e.g. Penrose 1989). And thermodynamics in general is, in the limit of very long timescales, determined by properties of the universe as a whole, i.e. by astrophysics and cosmology. Our goal in this note is to consider very simple cases of maximal informational resources available to advanced civilizations, either extraterrestrial or posthuman. We do not enter into any possible distinction between the two, since the ages of humanity, Earth and our Galaxy, as well as the pace of chemical evolution, suggest that there may be intelligent communities much older than ours even in our cosmological neighbourhood (Livio 1999).

2 An estimate of the maximal quantity of processed information

Let us consider various energy fields as potential sources of energy for information processing, using the assumption ("Cosmic Sum rule") that $\Omega = \Omega_\Lambda + \Omega_b + \Omega_{\text{CDM}} = 1$, where the first term corresponds to the vacuum energy, second to the baryonic matter, and the third to the (non-baryonic) cold dark matter (for the general cosmological considerations, see Peebles 1993). The best present estimates approach values $\Omega_\Lambda \approx 0.7$, $\Omega_{\text{CDM}} \approx 0.25$ and $\Omega_b \approx 0.05$ (e.g. Ćirković and Bostrom 2000, and references therein). One cannot do anything useful with the vacuum energy.¹ As far as CDM is concerned, it could conceivably be used as an energy source, since the annihilation of these cosmions and anticosmions (present in approximately equal numbers according to the standard theory) would produce potentially usable energy (for some consequences of annihilation, see Kaplinghat, Knox and Turner 2000). However, depending on the mass spectrum of cosmions, their galactic density is rather small, and since their interactions are by definition very weak, their gathering and separation for annihilation will pose huge engineering problems. If we consider the model of "posthumanity soon", then only usable matter field is the baryonic matter, in the local environment concentrated in the form of planetary systems.

We may use the Brillouin's (1962) equality for the upper limit of processable quantity of information (in bits):

$$I_{\text{max}} = \frac{\Delta E}{k_B T \ln 2} = 1.05 \times 10^{16} \frac{\Delta E}{T}. \quad (1)$$

Here, k_B is the Boltzmann constant. Both ΔE and T are functions of time, as well as of cosmological parameters Ω , Λ and H_0 . There are several important consequences of the Brillouin's inequality for cosmology. The amount of information available for processing in any causally connected region of finite proper size with trivial topology is necessarily finite.

As for the working temperature of posthuman computers, we may wish to consider two somewhat extreme models: (I) the first with $T = T_{\text{CMB}} = 2.730 \pm 0.014$ K (Staggs

¹On the contrary, it plausibly harms the energy budget by preventing, through the so-called cosmological "no-hair" theorem, the development and subsequent exploitation of the cosmological shear during the Hubble expansion (Gibbons and Hawking 1977).

et al. 1996)—indicating quick reaching of posthuman stage; additional cooling would require diverting the precious energy resources from computing itself—and (II) the second with

$$T = T_{\text{vac}} = \frac{\hbar c}{k_B} \sqrt{\frac{\Lambda}{12\pi^2}} = 3.2985 \times 10^{-30} h \left(\frac{\Omega_\Lambda}{0.7} \right)^{\frac{1}{2}} \text{ K} \quad (2)$$

indicating posthumanity in the asymptotic limit of physical eschatology. In this equation, Λ is the vacuum energy-density corresponding to the dimensionless cosmological density fraction Ω_Λ , and h is the dimensionless Hubble constant ($H_0 \equiv 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$).

Now we can write for the expendable energy:

$$\Delta E = \int_V q(\Omega_b \rho_{\text{crit}}) c^2 dV, \quad (3)$$

where V is the proper volume available to posthuman civilization and q is the energy extraction efficiency (between 0 and 1, and optimistically over 0.5). The usage of Ω_b is particularly useful when we consider possibility of posthuman civilizations of truly intergalactic size. Currently there is some confusion about the exact value of Ω_b , since the primordial nucleosynthesis inferences apparently conflicts with conclusions drawn from the microwave background anisotropy observations (e.g. Kaplinghat and Turner 2001). It is to be expected that this problem will be solved soon, but in the meantime we note that the exact value is inessential for our purposes. If we restrict ourselves to the model (I), that is, "posthumanity soon", we may neglect spatial variation of q and Ω_b (which would be present in other cases, say q is certainly different in intergalactic space from the one within galaxies), and using the definitional relation for Ω_b we get

$$\Delta E \approx q c^2 \int_V \rho_b dV. \quad (4)$$

Now, plugging this into (1), we obtain

$$I_{\text{max}} = \frac{q c^2}{k_B \ln 2} \frac{\int_V \rho_b dV}{T} = 3.5 \times 10^{36} q \int_V \rho_b dV, \quad (5)$$

in bits. If we wish to consider truly short-term posthuman civilization, we may state that the value of the integral is equal to

$$\int_V \rho_b dV = 2 \times 10^{33} \frac{\bar{M}}{M_\odot} n \text{ grams}, \quad (6)$$

where $n = 1, 2, \dots$ is the number of planetary systems controlled by our prototype posthuman civilization, and \bar{M} is the average mass of a planetary system in the Galaxy. The fraction in (6) is likely to be less or about 1.5, when mass of the hidden matter (like comets in the Oort cloud whose total mass is still uncertain; see Weissman 1983) in our planetary system is taken into account, as well as the possibility of harvesting some interstellar matter between systems. Taking all this into account, we reach the estimate of

$$I_{\text{max}} = 7 \times 10^{69} q n \frac{\bar{M}}{M_\odot} \text{ bits}. \quad (7)$$

An analogous estimate can be obtained for the case (II) of posthumans in the far future. This case will certainly be prone to much larger uncertainties of not only quantitative, but also qualitative nature. Therefore, we shall here give just a sketch and postpone the detailed analysis to a forthcoming study. To this end, we may generalize the expression (5) taking into account the changes in both resources and methods available to advanced civilizations during long cosmological scales

$$I_{\max}(t) = \frac{q(t) c^2}{k_B \ln 2} \int_{t_0}^t \frac{dt}{T(t)} \int_{V(t)} \rho_b dV. \quad (8)$$

Here, $V(t)$ denotes the physical (proper) volume of space available to the advanced civilization under consideration, and $T(t)$ is the evolution of the cosmic temperature ($T(t_0) = T_{\text{CMB}} = 2.730 \pm 0.014$ K). In this case, it is important to notice that the evolution of the equilibrium temperature of the universe in the context of physical eschatology is a problem not exactly solved to this day (approximate results for Einstein-de Sitter model are presented in Adams and Laughlin 1997), mainly because at very late epochs controversial sources (like the proton decay and Hawking radiation of an uncertain number of decaying black holes) come into play. Fortunately, we may be in position to know the asymptotic limit of the process of cooling of the universe, since it is determined by the temperature associated with the cosmological event horizon (Gibbons and Hawking 1977) in eq. (2). Since it can be shown that—if current estimates of the cosmological constant are correct—we have already entered the exponentially expanding (quasi)de Sitter phase (Ćirković and Bostrom 2000), we may use the simplest approximation of temperature decreasing as $T(t) = T(t_0) \exp[-H(t - t_0)]$, leading to the formal equalisation with (2) in $t = t_0 + (1/H_0) \ln[T(t_0)/T_{\text{vac}}] \approx t_0 + 69.58/H_0$, i.e. in about 1140 Gyr (for $h = 0.6$). As shown by Adams and Laughlin (1997; although only for the Einstein-de Sitter case), this is too pessimistic, since other photon sources will replace CMB as the determinants of the temperature of the universal heat bath. It will take probably many orders of magnitude larger time for the universe to reach the de Sitter temperature, but what is important is that there may be no further cooling. Thus, Dyson's (1979) idea about using a special form of hybernation for the expression in eq. (1) to diverge is unfeasible. That said, we leave considerations of the detailed solutions of eq. (8) to a subsequent work, which will benefit from our increased understanding of the future thermal history of the universe.

3 Discussion

We have estimated (within an order of magnitude) the information processing power of advanced extraterrestrial or future posthuman communities. Our estimate is conservative in the sense that we have ignored the complicated and not yet fully understood issue of dissipationless computation (see, for instance, Porod et al. 1984) and assumed classical limit of $kT \log 2$ dissipation per logical step. In addition, we have neglected the important issues of information *transmission*, noise and error correction (for a preliminary treatment of these, see the pioneering study of Sandberg 2000). All these issues should be covered in future, more realistic treatments.

It is worth noticing that numerical estimates reached above are quite conservative in comparison to the proposed fundamental information bounds, such as the holographic

bound (e.g. Sussking 1995)

$$I_{\max}^h = \frac{A}{4L_{Pl}^2 \ln 2}, \quad (9)$$

(where $L_{Pl} \equiv \sqrt{G\hbar/c^3} \approx 2 \times 10^{-33}$ cm is the Planck length) or the Bekenstein (1973, 1981) bound

$$I_{\max}^B = \frac{2\pi RE}{c\hbar \ln 2}, \quad (10)$$

where R is the radius and E the total mass-energy of the information cache. For instance, the equivalent of a holographic bound for the case of entire planetary systems from eq. (7) gives $I_{\max}^h \approx 9.8 \times 10^{76} (n\bar{M}/M_{\odot})^2$ bits, and the application of the Bekenstein bound to the same case yields $I_{\max}^B \approx 5.13 \times 10^{71} q(n\bar{M}/M_{\odot})(R/1 \text{ cm})$ bits (where one should keep in mind that in order for this bound to be meaningful, the size of the memory R has to be larger from its gravitational radius, which is about 3×10^5 cm per Solar mass). Parenthetically, we note that most of the treatments of cosmological limitations on computation to be found in the literature (e.g. Tipler 1986; Sandberg 2000) and on the Internet use the Bekenstein bound, which is certainly more realistic and practical, but does not look entirely sound from the conceptual point of view. The reason for such a disadvantage of the Bekenstein bound compared to the holographic bound is that the Newtonian gravitational constant G figures explicitly in the latter and not in the former. Since we believe that quantum gravitational degrees of freedom may contain a huge amount of information (and could be potentially exploited by advanced communities), a liberal approach would favor the usage of the holographic bound.

There are several reasons for pursuing this problem further. One is related to the confidence we may have in predictions of nonlinear dynamical systems by future computing devices. It is a well-known fact that (apparent) complexity of nonlinear systems increase at an exponential rate with time. No matter how advanced computing devices are employed in order to predict the behaviour of such systems, the prediction will break down at a particular timescale. One of the main factors determining this timescale is certainly the maximal amount of information which can be processed whatsoever during the computations necessary for prediction. But probably the most interesting issue to be solved by calculations such as these is the question of information cost of running large-scale detailed simulations of human environment. There are reasons to believe that advanced posthuman civilizations will run such simulations, which are sometimes aptly called "ancestor simulations" (Prof. Nick Bostrom, manuscript in preparation). It is clear, however, that the depth (or complexity) of such a simulation would be very sensitive to the computing power and information resources of a posthuman "director". In order to assess viability of this scenario, one should attempt to reasonably predict those quantities. On the other hand, it remains for computer and cognitive scientists, as well as sociologists, to answer the deep question of minimal informational cost of any realistic simulation of human consciousness and society.

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